SPACE TRUSS ASSEMBLY USING TELEOPERATED MANIPULATORS

By

Walter W. Hankins III, Randolph W. Mixon, and Howard C. Jones
NASA Langley Research Center
Thomas W. Burgess
Oak Ridge National Laboratory

INTRODUCTION

The level of man's activity in space and his utilization of it is increasing at a very high rate with an accompanying accelerating requirement for more and more astronaut EVA (Extra Vehicular Activity) to deploy, repair, service, and resupply orbiting facilities. It is likely that "people" will construct the Space Station from components carried into space on the shuttle and/or expendable vehicles, thus demanding even more of EVA astronauts. Human EVA is dangerous and inefficient; a better way of getting this work done is needed. A possible solution promoted recently by NASA research is to use automated and teleoperated machines, but these have many unresolved problems. Automated devices operate extremely well on earth-based assembly lines where they very precisely perform well defined, preprogrammed, repetitive tasks; but they do not perform so well when the environment is less structured and the required activity is impossible to timeline in detail, a priori.

Teleoperation, of course, having direct human control, is not so dependent on structured environments and precise timeline knowledge of the task, but will require a high level of manipulator dexterity and controlability for realistic space tasks. The Shuttle's Remote Manipulator System (RMS) has demonstrated a number of times its ability to perform certain basic teleoperator tasks. The tasks on the horizon, however, will certainly exceed the capabilities of the RMS by a wide margin. The construction, assembly, and checkout of the Space Station is an eminent example of such requirements.

One of the difficulties that NASA has had in deciding where and how to apply manipulators has resulted from not having a confident knowledge of their dexterous capabilities to perform complex, realistic space tasks or of how long the tasks will take to accomplish. The objective of the work reported in this paper was to address this issue by employing a teleoperated manipulator controlled by a highly-skilled, experienced operator to repeat a complex task already accomplished in space by EVA astronauts. This would both show that it could be done and provide as well a data base of task completion times. The task chosen was the Access I truss assembly which was done by EVA astronauts on STS-61b in November 1985. That flight experiment proved that astronauts can perform the basic operations required to assemble trusses in space.

The trusses are of the general type expected to form the framework of Space Station. The truss elements used were, however, about one fourth the size of the anticipated 5 meter lengths of the full scale ones on Space Station. Having chosen a task to perform, the next concern was what manipulator system to use. Probably the most skilled, dexterous, and experienced examples of teleoperated remote handling are to be found in operations involving the handling of radioactive materials. Because of this, Oak Ridge National Lab (ORNL) which has very extensive experience in the processing of nuclear materials was solicited to supply both skilled operators and its dual arm, master/slave manipulator [Central Research Lab (CRL), Model M-2] for use in these tests.

The ACCESS I Flight Experiment

The ACCESS I (Assembly Concept for Construction of Errectable Space Structure) was a structural assembly flight experiment intended to study and verify the ability of astronauts to assemble in space a repetitive truss structure representative of the type likely to become a part of Space Station. It was launched in November 1985 as a part of the Shuttle Mission STS-61b. During the ACCESS EVA (fig. 1) astronauts performed a rehearsed assembly line technique using a construction fixture as an aid. The on-orbit data which resulted has provided a basis for comparison and correlation with neutral buoyancy simulations practiced in preparation for the flight experiment.

The truss was assembled from basic hardware (figs. 2 & 3) which consisted of interchangeable, aluminum nodes and columns which can be snapped together to form connected bays of structure with a triangular cross section as shown in fig. 4. The horizontal and vertical members were 4.5 ft long and the diagonals 6.36 ft long with a two position locking sleeve on each end of each member. The nodes (fig. 2) each had six nubs to which the columns could be attached. The columns were mated to a node by sliding back the sleeve on the column's end and with a side approach intermeshing the fingers on the node's nub with those on the column's end. Finally the sleeve was slid back over the joint to make it secure.

Fig. 4 shows the equipment and general setup for the flight task with the astronauts in their designated places (no.'s 1 & 2). The nodes and columns were supplied from the canisters (no.'s 3, 4, & 5) which were located so that the astronauts did not have to leave their stations to build the truss. They used the assembly fixture (no. 6) as a frame on which to place and hold parts as the truss sections were being put together. Nodes were slid up the guide rails (no. 7) from the bottom to latching positions on the fixture. The columns were attached to these to form a finished bay which was subsequentially released and slid up along the guide rails to a new latched location to make room for the assembly of an additional bay on the lower half of the fixture where the raised bay had been.

Two bays at a time could reside on the assembly aid. The fixture was rotated by the astronauts at specific intervals during the construction to provide themselves access to parts of the truss they were supposed to be working on. Each astronaut had very specific duties in the assembly sequence which were repeated in cycles until ten bays of structure had been completed.

Equipment and Facilities

The Access truss remote handling experiments were performed at Oak Ridge National Laboratory's (ORNL's) Remote Operation and Maintenance Demonstration (ROMD) facility. The ROMD facility was developed by the U.S. Department of Energy's Consolidated Fuel Reprocessing Program to develop and demonstrate remote maintenance techniques for advanced nuclear fuel reprocessing equipment. Central Research Laboratory's model M-2 servomanipulator which was used for the Access teleoperator task is a dual-arm, bilateral force reflecting, master/slave servomanipulator developed jointly by CRL and ORNL and represents the state-of-the-art in commercially available teleoperator manipulators. The M-2, in operation since FY 1983, incorporates a distributed, microprocessor-based digital control system and was the first successful implementation of an entirely digitally controlled servomanipulator. Two major assemblies comprise the M-2: (1) the slave package shown in fig. 5 and (2) the master control station of fig. 6. The slave performs "man-like" handling tasks in the remote environment. The package consists of a pair of force-reflecting servomanipulator arms, three television viewing cameras, lighting, and a 230-kg (500-lb) capacity auxiliary hoist. Each slave arm has a 23-kg (50-lb) continuous capacity, a 46-kg (100-lb) time-limited (peak) capacity, and six degrees-of-freedom (joints) which are driven by brushless dc servomotors. The servomotors are mounted at the base of the arm and transmit power to the three degrees-of-freedom closest to the base through gears and linkage, and to the remaining three degrees-of-freedom plus the end-effector jaws by cable and pulley arrangements passing through arm tubes. Each servomotor has a servoamplifier and joint processor mounted in racks on the slave. The slave arm joint processor communicates with its respective master arm joint processor through a high-speed digital serial link. Basic control is through a closed-loop, position-position error technique.

Master-to-slave arm control is in real time with slave arm tip velocity capabilities up to 152 cm (60 in) per second. The minimum slave arm loading which can be detected or "felt" at the master control arm is on the order of 1 pound or 1 percent of peak capacity. All arm joints are force reflecting.

Operator viewing of the remote work site is provided by CCTV cameras mounted on the slave package. These include two boom-mounted cameras with four positioning degrees-of-freedom (pan, tilt, boom extend-retract, and boom pivot) and motorized lens controls (zoom, focus, and iris); and one fixed camera mounted between the slave arms. The cameras provide standard resolution color video to 19-inch monitors at the master control station. The two boom-mounted cameras one on each side, provide orthogonal views for depth perception and viewing flexibility. The lower camera produces a wide angle view of the work site from a fixed position to give additional viewing information and information concerning master-to-slave arm spacial relationships.

Control of the slave is performed by a single operator from the master control station which consists of a pair of master arms, three 19-inch color television monitors, and an operator console (see fig. 6).

The six degree-of-freedom master control arms are kinematic replicas of the slave arms with each having a 25 lb. peak capacity. The handle on the master is a pistol grip and trigger type that provides slave tong control. Switches on the handles allow the operator to perform such functions as slave tong lock, slave arm lock, master-to-slave "all joint" indexing, and electrical tool power control without releasing the handle.

The operator interfaces with the control system for other functions primarily through a CRT and touch-screen mounted in the operator console. Operating mode selection, force-reflection ratio selection, camera/lighting control and system status diagnostics are available through this interface.

Camera and auxiliary hoist controls are also on the operator console. A joystick used for overhead camera positioning has spring loaded potentiometers to provide camera lens zoom, focus, and iris control.

Camera views selected to the three control station monitors are primarily the onboard slave camera views but can also be selected from several other facility and transporter-mounted cameras as desired by the operator. In addition, for this study, three other television monitors were arranged at the M-2 control station and could similarly be selected. They provided wide angle views (typically a field of approximately 10 ft by 10 ft) of the worksite which assisted operators in seeing and orienting the entire truss strut length.

The handling and assembly of the truss struts and nodes were performed without modification to the ACCESS components or the remote handling equipment. The manipulator tongs were fitted with standard finger pads. A flat-faced finger and a V-groove type finger were used on each tong. This finger combination produced a good grip on the tubular struts and countered any pivoting action at the finger contact points.

Remote handling operations were performed at a four-to-one slave-to-master force reflection ratio as preferred by the manipulator operators, although a range of ratios from 0 to 8:1 were available at their option.

Teleoperated Assembly of the ACCESS I Hardware

Experiment Procedure

Hardware from the ACCESS I flight experiment was taken to the ORNL and set up as shown in fig. 7 where it could be operated upon by the M-2. The assembly fixture (no. 1), actual flight hardware, was mounted on a wooden support fixture (no. 2) built originally for checkout of the ACCESS flight hardware. The nodes and struts were ones used by astronauts in water immersion training in preparation for STS-61b, but otherwise identical to the flight hardware.

During data runs the M-2 was alternately placed in each of the two assembly positions occupied by the astronauts [see fig. 1 and (1), (2) of fig. 4] in the flight experiments and from these positions, it along with a human subject in the other position (fig. 8) repeatedly constructed two bays (the first two) of the ACCESS truss. The manipulator's base was not allowed to translate while runs were taking place. After each construction the two bays were manually disassembled in preparation for the next run.

Two manipulator operators with extensive experience in remote handling controlled the M-2, each operator doing eight repetitions of the construction task in each operating position. Operators and operating position were rotated to distribute over all the runs the effects of learning and to minimize operator boredom. Each test subject performed two consecutive data runs in each position after which the manipulator was moved to the other operating position where the cycle was repeated.

A test procedure was prepared detailing the step by step subtasks of each builder to assemble the two bays. During the course of a run the manipulator operator performed alone all the required teleoperations including master/slave control of both manipulator arms as well as remote operation and adjustment of TV cameras and selection of desired remote site TV images on control station monitors.

The operator at the lower station had about 70 percent of the work to do including retrieving and installing all nodes, retrieving and installing all verticals, and retrieving and installing 2/3 of the horizontals. The node canister (no. 5) and the lower strut canister (no. 4) from which he got these parts are shown in fig. 4. The nodes were installed by sliding them from the bottom up the tapered guide rails on the assembly fixture. At the beginning of each construction the three top nodes of the first bay were already in place. In addition to the above duties the lower station operator received diagonal struts handed to him by the operator at station #2 and attached them to appropriate nodes. Finally he was responsible for rotating the assembly fixture as needed for both parties to have required access to truss sections being worked on. In the flight assembly of ACCESS I either party could rotate or assist in rotating the fixture as needed; however, it was felt that if the same option were available in these studies that the person-half of the assembly team would likely end up doing all the rotating regardless of the station he was manning. Thus, station #1 was assigned to do it all the time while station #2 was never to do it.

The builder at station #2 had less work to do (about 30 percent of the total) including retrieving the diagonals from the upper strut canister (no. 3) and handing them to the operator at station #1 while connecting one of their ends to the upper nodes. He also installed the upper set of three horizontals on the first truss bay and completed upper connections of verticals after they had been installed on the lower nodes by the station #1 operator. Finally upon completion of the bay #1 assembly, station #2 released the truss latch which held one node of the lower bay firmly in place. He then raised that entire bay one level and secured it with the latch holding one of its lower nodes. The construction of the second bay then took place where the first bay had been.

Operators were given breaks frequently, these generally occurring between construction of each pair of bays.

The ACCESS struts had to be aligned in a particular way for their ends to mate with the nodes, but their symmetrical appearance, especially through closed circuit TV, made doing this very difficult. The problem was addressed by marking the struts to ensure reasonable attachment times. Marking was accomplished by putting a thin line on one side of the column along its major axis (see fig. 3) such that if the operator could see the mark centered in the manipulator jaws as he moved the column toward the node to which it was to be attached, then the alignment was approximately correct. To assist in quickly finding the line an additional mark in the form of a diamond was printed on the opposite side of the colunm.

Data acquisition consisted of video taping to provide a visual record, real time observations of task completion times as well as certain other task element completion times, and observations of task performance errors. Time synchronized video recordings were made of (1) the M-2 operator's primary TV view at the M-2 console and (2) a general overall view of the assembly at the test site. Two observers one at the assembly site and the other in the M-2 control room kept these records and operated the video tape recorders. The "primary view" was recorded at the discretion of the control room observer as the one he believed at the time to be the one being used by the manipulator operator. Thus, it was subject to change on a continuous basis. Performance errors are deviations from proper performance of the task consisting of such events as dropping parts or taking actions which require the task to be stopped. When one of these was recorded by an observer, he, at the same time, noted specifically what had happened.

Runs were begun with both the person assembler and the manipulator assembler poised to begin their first operation. The person-assembler gave a countdown to begin each run to all other participants over a radio headset. At this point, the components required to build the structure were all in their respective canisters and everything ready to go. Runs ended for data taking purposes when the tongs of the M-2 had released the final assembly component in the last assembly step.

RESULTS AND DISCUSSION

The notion that a complex task such as building the ACCESS I truss could be done with manipulators was uncertain and unproven prior to the studies of this report, although many believed such accomplishments were possible. These experiments have proven by demonstration that tele-operated manipulators have the required dexterity to perform the ACCESS task and by implication other similiar ones. In addition, a data base of times required to complete the task have been recorded. After eight runs the subjects at ORNL were able to assemble the ACCESS truss in a continuous, almost routine fashion, generally without incident. The bar graph of fig. 9 gives a comparison of assembly times for a variety of conditions including one-G, shirt sleeves; ground-based water immersion simulation with pressure suits; Shuttle flight; and teleoperated assembly at ORNL. All data are normalized to the completion of two bays. The teleoperator assembly time shown is an averaged figure computed from the last three runs of both M-2 operators (a total of twelve runs). This figure was used because it was expected that learning effects would be greater in the earlier runs, thus the later runs would be a more accurate indicator of stable teleoperator performance. The figure for the water immersion facility is an average of times from Johnson Space Center's Weightless Environment Training Facility (WETF) and Marshall Space Center's Neutral Buoyancy Simulator (NBS) and include some results from development tests with untrained subjects. As can be seen the teleoperator assembly took about three times as long as did the pressure-suited astronauts in space to achieve the operation. The teleoperator time is very good, however, when one considers that neither the hardware being assembled nor the manipulator itself had been designed to accommodate this task. A rule of thumb at ORNL is that tasks which require no more than eight times as long to do with the manipulator as for people to do directly are well suited for remote handling. An average time computed from the two very best runs made at each of the two stations, was only about two and one half times as long as for the astronauts.

The curve of fig. 10 summarizes the task completion times on a generally chronological basis for the subjects individually as well as their average. Each point represents a total time to build both bays. The curve for individual operators are averages of the runs they made at both stations: i.e., the point for operator #1, trial #1 is an average of his first run at station #1 and his first run at station #2. As can be seen there is a general decrease in times to complete the task with increasing replications indicating learning as would be expected. The effect seems to be much greater with subject #2 than with #1, although it is certainly there for both and readily shows up in the curve for their combined performance.

The average time to complete the task for both operators at each of the stations individually are shown in fig. 11 which presents these in a chronological progression. As before, learning effects are evident and seem to be somewhat more pronounced at station #2. The time required at station #2 was much less than at station #1. This is reasonable considering that there is much less work to do at station #2. In addition, acquiring and installing the nodes (which is second only in difficulty to installing the horizontal struts) is unique to station #1. Moreover, 67 percent of the horizontals themselves are installed at station #1.

The other performance measure applied to the teleoperator runs was the number of truss components dropped during the runs. Fig. 12 shows the total number of components dropped and is broken down by test subject, by node, and by column. Fig. 13 provides the distribution of these on a run by run basis. Note that 14 of the 18 drops occurred on three of the runs leaving an average of .8 drops/run for the other five runs with three of these runs actually having no drops at all. Data in this figure combine nodes and columns at both stations as well as subjects, i.e., the five drops for run #5 were computed as the total of two nodes at station #2 and one strut at station #1 for subject #1 on his fifth run at both stations and two struts at station #2 for subject #2 on his fifth run at that station. No nodes were dropped by subject #2 on his fifth run at station #1. On each run 6 nodes and 12 columns were handled at station #1 and zero nodes and nine columns at station #2. From this, it may be noted that each data point in fig. 13 includes 54 handled truss elements or opportunities to drop an element [18 @ station #1 + 9 @ station #2) * 2 subjects = 54]. Thus the maximum number dropped (5) on a run as shown in fig. 13 was only about 9.3 percent of the maximum possible. Over all of the runs only 4.2 percent of the elements were dropped.

All of the nodes that were dropped were dropped at station #1, if for no other reason than that they were not handled at all at station #2. On the other hand, all of the struts that were dropped, but one, were dropped at station #2. Furthermore, all but one of the incidents of dropping struts at station #2 were drops back into the strut canister resulting from strut ends slipping out of the end effector jaws. A fair amount of this problem came from the fact that the ACCESS hardware was not designed for manipulator handling; this is especially true of removing components from canisters. The nodes were tightly packed into their canister making it very difficult to grasp them with the large, nondexterous, parallel-jaw end effector. Fig. 14 shows the open node canister. There was a similiar problem with the struts, but not as severe, because the clearance was greater among them. Unlike the EVA astronauts, the teleoperator at Oak Ridge had to deal with gravity which in the case of the vertically located strut canister at station #2 turned a little slip in grasp into a drop back into the canister. A vertical extraction was also required at the node canister. The other strut canister located at station #1 (see fig. 4), (no. 4) was oriented for extraction in the horizontal plane and apparently because of the orientation had no drop-back problem. Both the node canister and the vertical strut canister were located near the reach limits of the manipulator magnifying the grasp problem. The remaining drop of a strut at station #2 did not take place as a result of an end effector grasp problem but rather occurred while the teleoperator was passing a diagonal to its human construction partner and happened because of the mistaken belief that the human had grasped it. The only dropping of a strut at station #1 occurred on the same run that two nodes were also dropped and probably occurred because of fatigue (the M-2 operator said fatigue was the problem and the observers agree). The components dropped on this run were the most dropped by an M-2 operator on any one run. Of the remaining six dropped nodes two were drops back into the canister, one resulted from the inadvertant disengaging by the operator of the grip lock on the hand controller, and the other three were probably victims of handling complications. The nodes were difficult to deal with. After they came out of the canister they had to be reoriented by grasping, turning, passing off, and regrasping using both end effectors to poise them for placement on the guide rails.

Work load was very high during these experiments. The requirement for dual arm activity was much greater than the operators were accustomed to. The task was intense, perhaps overly so, because of the competition with the clock. For at least these reasons, operators reported fatigue to have been significant throughout the course of the tests.

Discussions with the subjects and observations by those conducting the tests have identified several modifications of the hardware which if implemented should positively influence the teleoperator performance of this task:

1. Flat grasping points on the columns and the nodes. These would serve to produce grasping compatibility between work pieces and end effector and as well provide a means for incorporating indexing to expedite alignment.

2. Sleeves on the column ends without mechanisms which hold them in cocked and locked back positions.

3. Good audio from the remote site. Sound would provide an additional channel of information to the operator without imposing any requirements for directing attention. Completion of operations would be indicated by sounds such as the snap of the column sleeve sliding over the node end at the connection or of the operation of the latch securing the position of the upper bay on the construction fixture. Undesired hardware impacts would be heard, etc.

4. Better markings on struts to indicate orientation.

5. Canisters located and oriented to accommodate the manipulator. The canister location should be far enough away to permit extraction of the columns without the manipulator pushing them into its own base and jamming. The distance away that the canister is located should not, however, be so far as to cause greatly diminished dexterity because of proximity to reach limits.

CONCLUDING REMARKS

Teleoperator experiments were conducted which have demonstrated that a realistic, complex task, typical of those accomplished on-orbit by EVA astronauts, can be done in a smooth, timely manner with manipulators remotely controlled by humans. The real concerns were: 1) Do manipulators have sufficient dexterity for these tasks? 2) Can sufficient information from the remote site be provided to permit adequate teleoperator control? 3) Can reasonable times relative to EVA times be achieved? and 4) Can the task be completed without frequent and/or damaging impacts among the task components and the manipulators? Positive answers were found to all of these concerns. Task times, operator fatigue, and smoothness of operation could be improved by designing the task components and the manipulators for greater compatibility.

Because of certain very specific operations such as turning and sliding the sleeves on the column ends, and holding the latch open while raising the first bay; coordinated dual-arm manipulation was definitely a requirement in this task. However, there were strong indications as well that the general task may not have been doable without two arms even if modifications had been made to accommodate with one arm the idiosyncrasies of these particular subtasks. Especially in one G, final alignment of the horizontal columns to mate with the node ends benefits greatly from being able to support the column simultaneously at both its ends. Two arms permit rotation about specific points by one arm holding

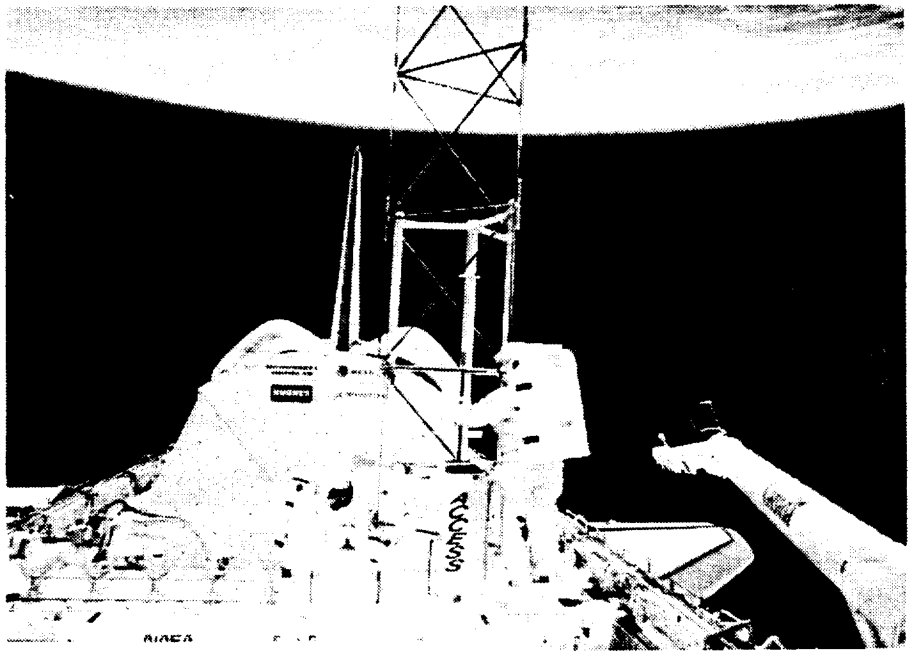

Figure 1 Astronauts Ross and Spring Assemble ACCESS on STS 61b

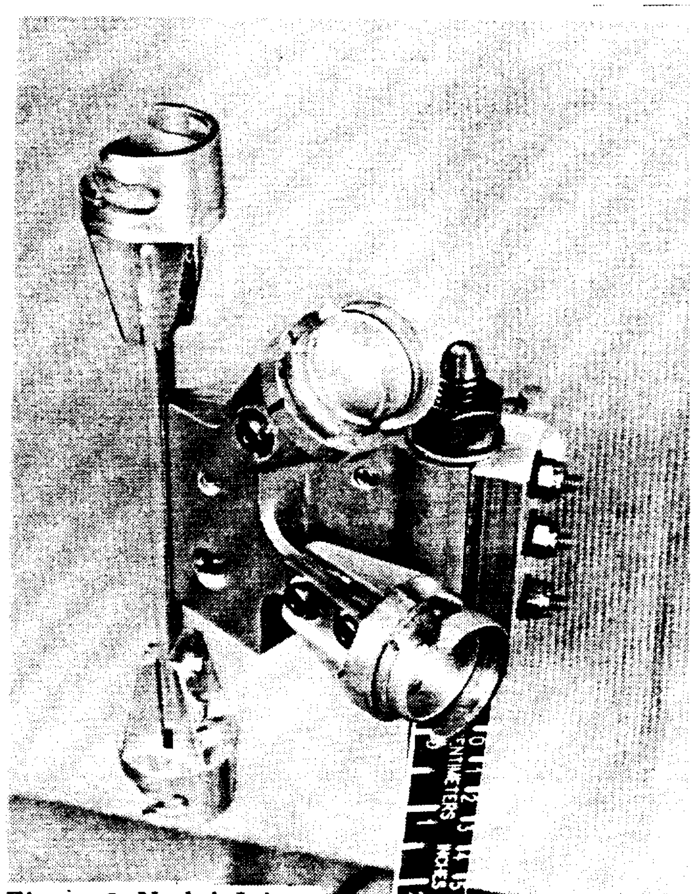

Figure 2 Nodal Joint

C-5

the part at that point while the other generates a moment about it. Node reorientation is facilitated by using one arm to hold while the other regrasps, etc.

The data recorded supplements a data base of performance metrics for the same task done in the water immersion training facilities as well as space flight and provides management with a objective basis for deciding how and where to apply manipulators in space.

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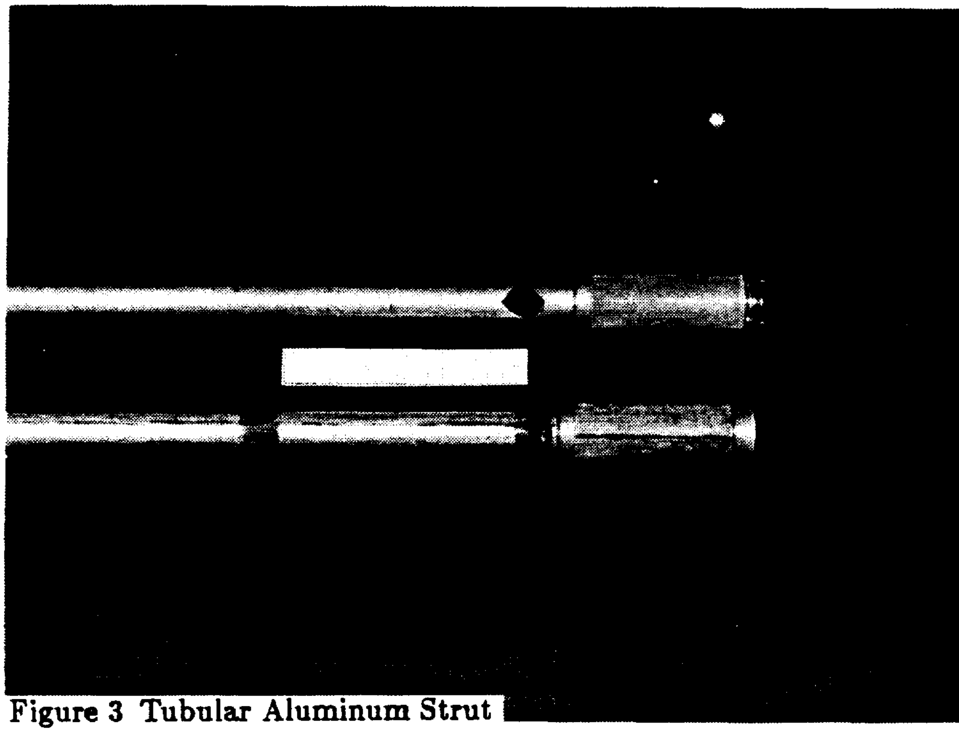

Figure 3 Tubular Aluminum Strut

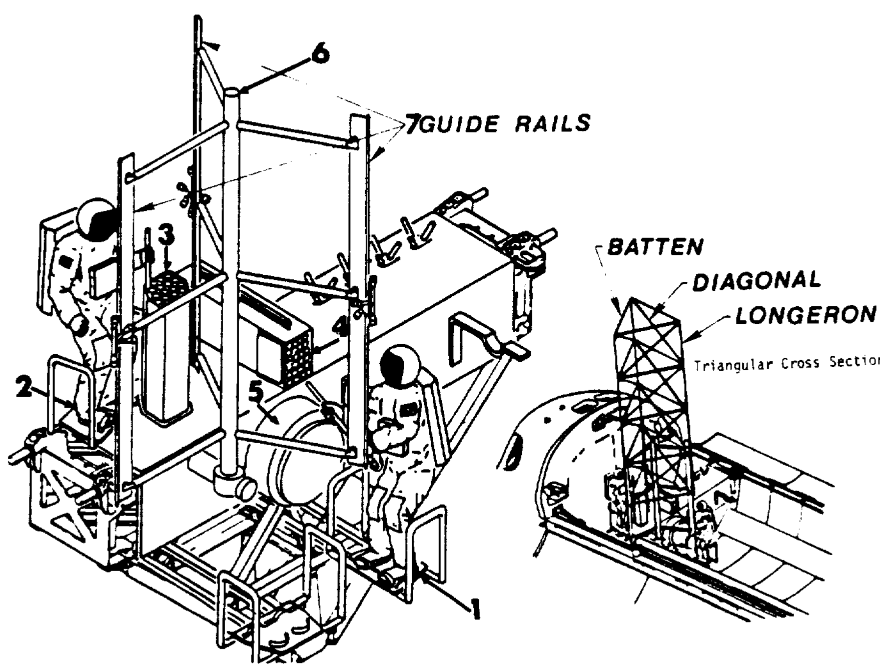

Figure 4 Schematic Showing EVA Construction of ACCESS Truss on Assembly Fixture

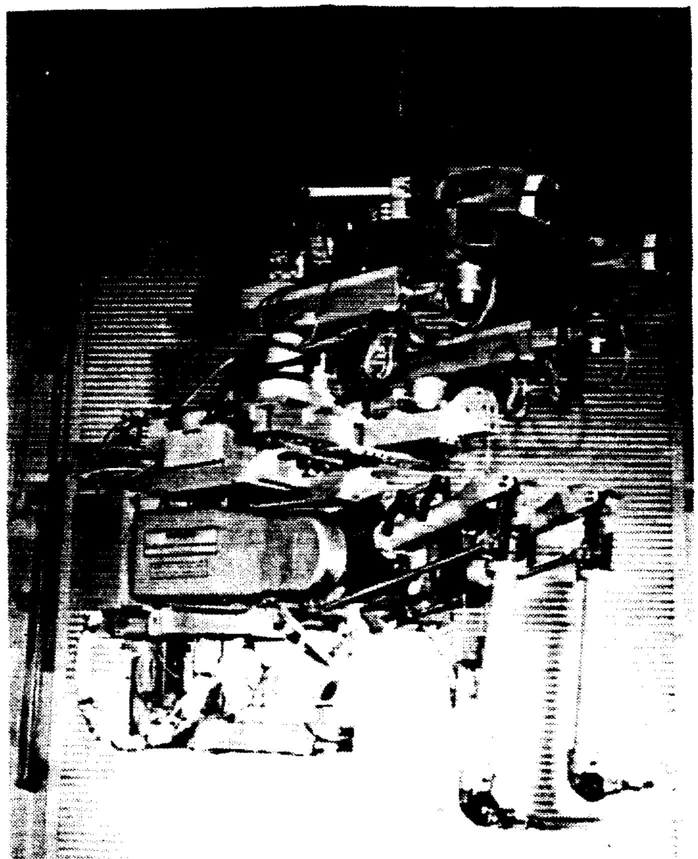

Figure 5 CRL Model M-2 Servomanipulator Slave Package

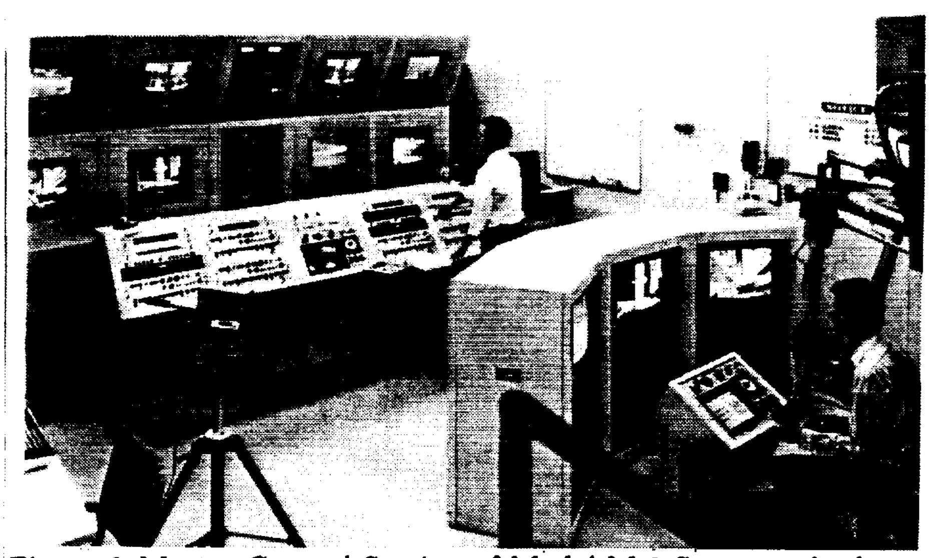

Figure 6 Master Control Station of Model M-2 Servomanipulator

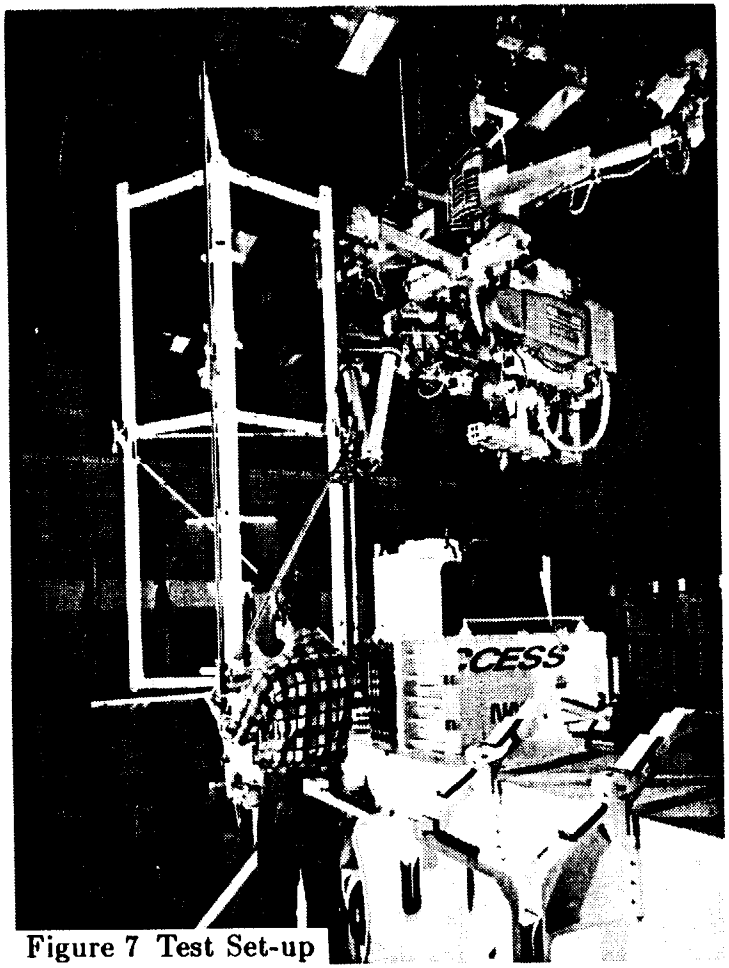

Figure 7 Test Set-up

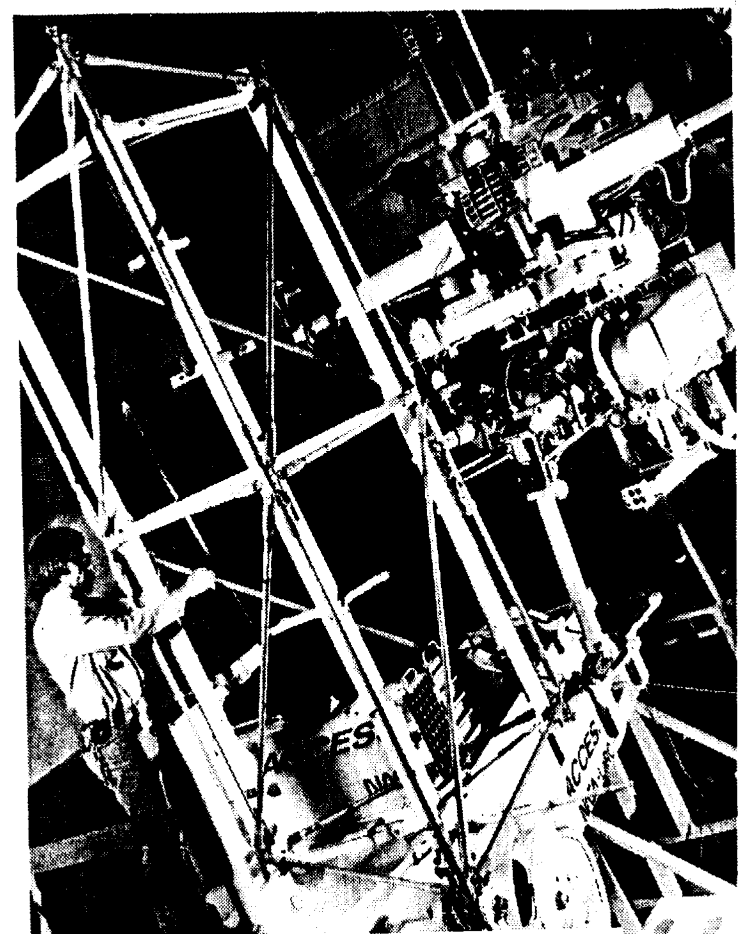

Figure 8 Man and Manipulator Cooperate to Construct Two Bays

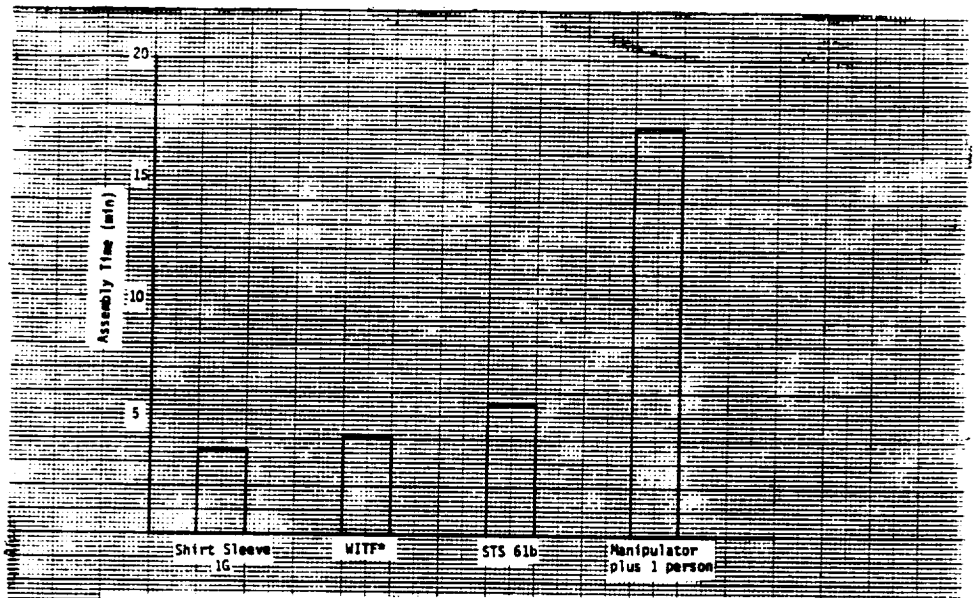

Figure 9 Comparison of Assembly Time in Different Facilities

*Water Immersion Training Facility

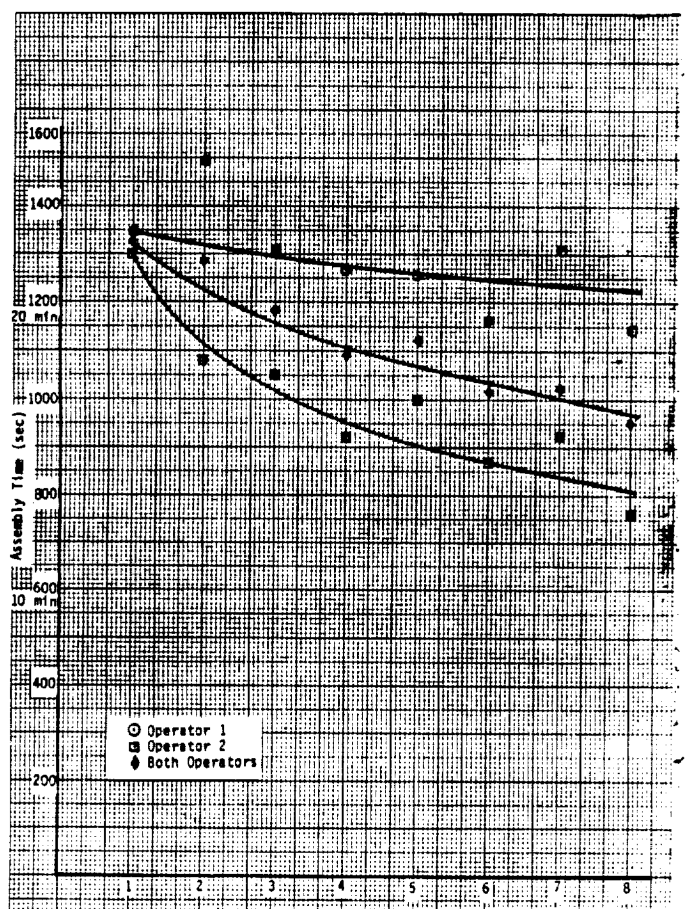

Figure 10 Comparison of Average Times for Each Operator

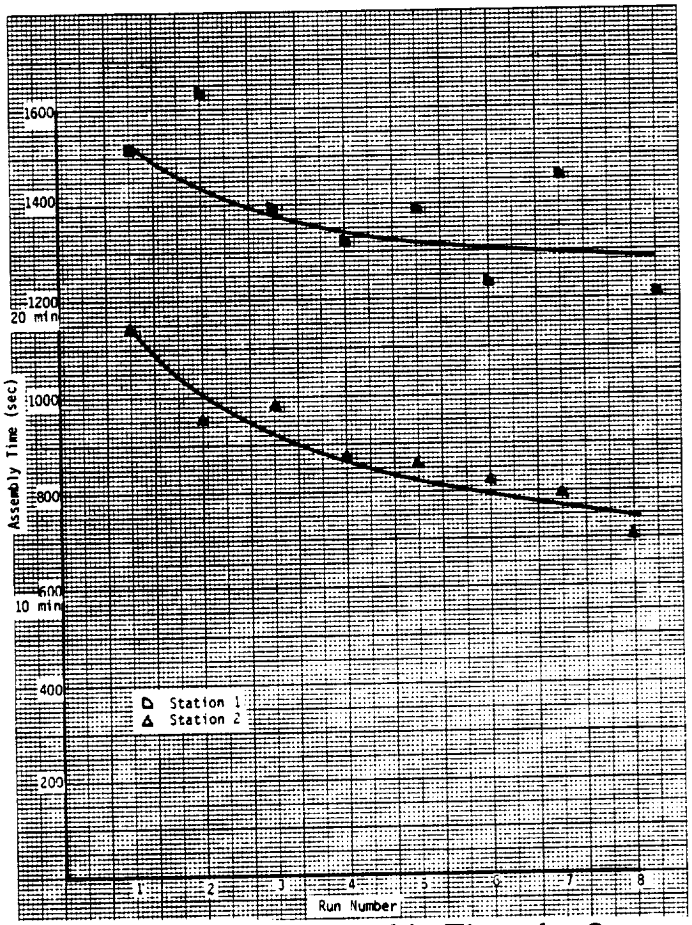

Figure 11 Average Assembly Times by Operator

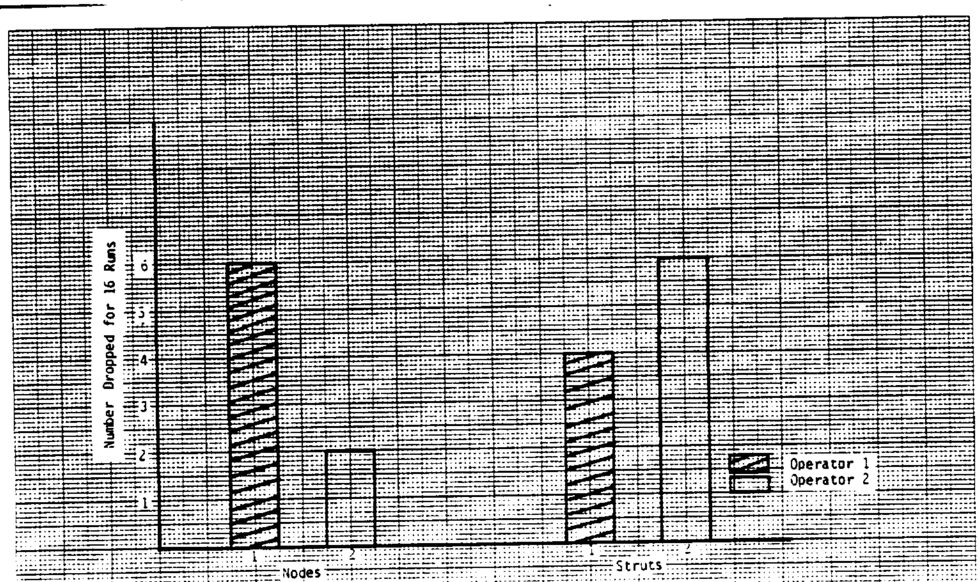

Figure 12 Comparison of Components Dropped by Components Type and Operator

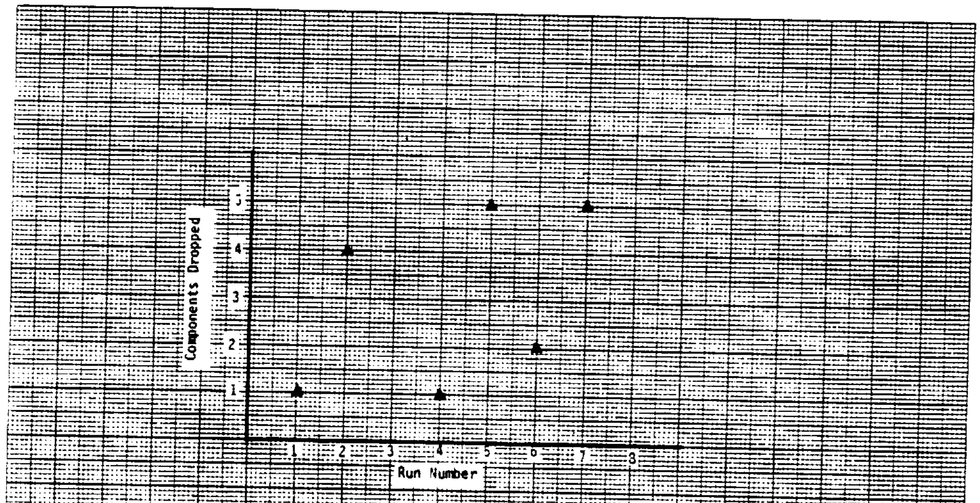

Figure 13 Total Dropped by Run

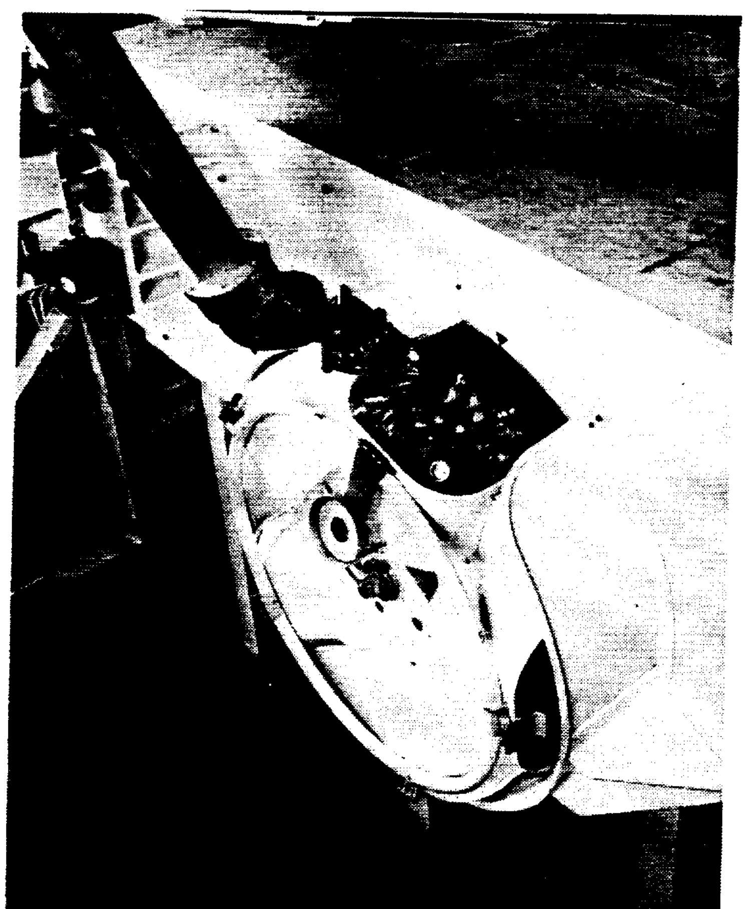

Figure 14 Node Canister